GOOD ABUNDANCES FROM BAD SPECTRA: II. APPLICATION AND A NEW STELLAR COLOR-TEMPERATURE CALIBRATION

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Running Head : Good Abundances from Bad Spectra

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ABSTRACT

Stellar spectra derived from current multiple-object fiber-fed spectroscopic radial-velocity surveys, of the type feasible with, among other examples, AUTOFIB, 2dF, HYDRA, NESSIE, and the Sloan survey, differ significantly from those traditionally used for determination of stellar abundances. The spectra tend to be of moderate resolution (around 1 Å) and signal-to-noise ratio (around 10-20 per resolution element), and cannot usually have reliable continuum shapes determined over wavelength ranges in excess of a few tens of Angstroms. Nonetheless, with care and a calibration of stellar effective temperature from photometry, independent of the spectroscopy, reliable iron abundances can be derived.

We have developed techniques to extract true iron abundances and surface gravities from low signal-to-noise ratio, intermediate resolution spectra of G-type stars in the 4000–5000 Å wavelength region. The theoretical basis and calibration using synthetic spectra are described in detail in another paper (Jones, Gilmore and Wyse 1995). The practical application of these techniques to observational data, which requires some modification from the ideal case of synthetic data, is given in the present paper. An externally-derived estimate of stellar effective temperature is required in order to constrain parameter space sufficiently; a new derivation of the $V-I$ – effective temperature relation is thus an integral part of the analysis presented here. We have derived this relationship from analysis of available relevant data for metal-poor G dwarfs, the first such calibration. We test and calibrate our techniques by analysis of spectra of the twilight sky, of member stars of the cluster M67, and of a set of field stars of known metallicity. We show that this method, combined with our new color-temperature calibration, can provide true iron abundances, with an uncertainty of less than 0.2 dex over the range of metallicity found in the Galactic thick and thin disks, from spectra obtained with fiber-fed spectrographs.

1. INTRODUCTION

Multi-object optical fiber-coupled spectrographs are increasingly being used for radial-velocity surveys of faint objects. Such surveys generate very many spectra, each of which is without reliable continuum flux calibration (due to the difficulty of atmospheric dispersion correction with fibers), and of lower resolution and signal-to-noise ratio than are typically used for stellar abundance determinations. Nonetheless, useful chemical abundance data can be derived from such spectra. We have described in Paper I (Jones, Gilmore and Wyse 1995) a method developed to measure iron abundances and surface gravities from relatively low signal to noise ratio, intermediate-resolution (around 1 Å) spectra of G-type stars, in the 4000–5000 Å wavelength region. The details of the theoretical framework and its calibration by means of the analysis of synthetic spectra are given in Paper I. The present paper concerns the practical application to observational data. Gilmore, Wyse and Jones (1995) apply these methods to a sample of faint ($15^m < V < 18^m$) F- and G-type stars a few kiloparsecs below the Galactic plane to determine the thick disc chemical abundance distribution.

The strengths of absorption lines in the atmosphere of a star depend on the effective temperature, the stellar surface gravity, and the abundances of different chemical elements. In principle, all these parameters may be measured, given high enough quality data. Lower signal-to-noise ratio data require some compromises. For example, it is potentially dangerous to attempt to solve for both temperature and metallicity for late-type stars, since errors in these two parameters are highly correlated, due to the strong sensitivity of metallic line absorption to both parameters. The effective temperature of a star may be estimated from non-spectroscopic data, such as $V - I$ colors, leaving gravity and elemental abundances as the determining parameters of the strengths of absorption features. Defining absorption indices of different sensitivities to abundance and gravity allows a solution for the two parameters to be obtained. This is the philosophy behind the approach advocated here. The problem may be further simplified if one can estimate the surface gravity of the star, for example from an expectation of the evolutionary state, reducing the analysis to a study of the relationship between line strength and elemental abundance. This allows poorer quality data to provide chemical abundance estimates.

Spectroscopic indices sensitive to iron abundance and gravity have been defined from a set of narrow (few – several Å wide) wavelength bands, with adjacent comparison bands. The theoretical calibration of this technique, presented in paper I, indicated that, given a photometrically determined effective temperature, it should be possible to derive relations between iron abundance and gravity from each individual absorption line index, and that each of these two stellar parameters may be determined, provided that the noise in the intensity data is not too great. Further, a single abundance indicator may be defined for the reduction of noisier data; with the input of values for both the surface gravity and the effective temperature, this single indicator is able to provide useful iron abundance information from spectra having signal-to-noise ratios as low as 10 per resolution element.

2. DETERMINATION OF IRON ABUNDANCE

2.1 The Basic Analysis Methods

As discussed in paper I, 80 flux bands were chosen as the bases of metallicity- and gravity-sensitive absorption-line indices, akin to equivalent widths. These are given in Table 1 (metallicity) and Table 2 (gravity), together with the set of eleven metallicity and metallicity-gravity indices which have been defined from these (Table 1), and five ionic gravity indices (Table 2). The technique for estimating the iron abundance of a given star rests upon the comparison of the values of these indices, or a suitable combination of them, measured from an observed spectrum, with those of synthetic spectra with effective temperature (and later, gravity) chosen to bracket the star under study.

Synthetic spectra were computed assuming LTE for a range in stellar parameters – metallicity, gravity and effective temperature – covering the grid given in Table 3, giving a total of 100 stellar models. These are scaled from the standard Holweger-Müller (1974) solar model atmosphere, adopting solar ratios for the relative abundances of the heavy elements; any effects of non-solar element ratios are taken account of by the empirical calibration below. The data covered the wavelength ranges 4025–4090 Å , 4500–4690 Å and 4870–5000 Å , these sections being selected as the most promising for iron abundance indices in the blue region of the spectrum, whilst also being free of substantial molecular line absorption. All atomic lines listed in the Moore, Minnaert and Houtgast (1966) solar line compilation were included in the synthesis calculations. Oscillator strengths were computed from the solar spectrum for most lines, supplemented by selected accurate laboratory data. Details of the synthesis process, including the choice of solar, stellar and atomic data, are given in Paper I and in Jones (1991).

The fluxes in the narrow wavelength bands are somewhat sensitive to the resolution of the spectrum, as a result of the extent to which features at the edges of the bands are included. In order to allow the analysis methods to be used for the reduction of spectra of differing resolutions, flux data were computed appropriate to a range of resolution, from 1.0 Å to 2.5 Å full-width at half-maximum in 0.1 Å intervals. Each theoretical spectrum was convolved with a Gaussian profile of an appropriate width to represent instrumental effects adequately. The validity of this broadening function, and of its width, were gauged by the study of calibration arc-lamp lines. A fixed resolution was adopted across the spectrum; the actual variation of the resolution across the observed spectra of interest was generally a few percent (see section 4.1 below), so this assumption is reasonable. Residual fluxes, where 'residual' means the ratio of the observed value to that which would occur in the absence of absorption, were calculated by integrating the residual intensities over wavelength across each flux band. Each set of 8000 synthetic fluxes corresponding to a particular resolution was stored in a separate data file; the analysis methods can be tailored to the resolution of a particular observed spectrum by the choice of the synthetic flux data file.

A difficulty with multi-object fiber-fed spectrographs, which complicates comparison of synthetic and observed fluxes, is the presence of scattered light in the spectrograph and detector, adding a locally-variable background signal to the reduced spectra. Care is essential to correct reliably for this scattered light. For the spectra of relevance here the optimum sky background subtraction algorithm applies a local scattering correction (see Wyse and Gilmore 1992), obviating the need for any special processes to handle scattered light in the abundance analysis.

2.2 Evaluation of the Indices

An observed spectrum is calibrated in wavelength, the stellar radial velocity is determined by cross-correlation against templates of known velocity (the present data provide velocities accurate to 5–10 km/s), the spectrum is corrected to a laboratory rest frame, then normalised to a constant continuum level. The continuum variation is removed by fitting distinct low-order polynomials to sections of the spectra, followed by a smoothing of the final fit. The errors of this procedure are usually less than 10 % in intensity over 100 Å at short wavelengths, where molecular bands are strong, and considerably less than this at longer wavelengths. The errors in the normalisation will tend to be greatest in spectra of stars which experience strong absorption, in effect in cool stars of near-solar metallicity. The irregularities remaining after continuum flattening occur over a sufficiently broad wavelength scale that the indices defined here will not be affected appreciably. This feature was of course a defining requirement in our development of this method.

The data reduction process, given digital data, has the effect that not all pixel boundaries are identical from spectrum to spectrum, and nor will there necessarily be identity between pixel boundaries and the boundaries of the theoretically-defined indices. We obviate potential difficulties here by ensuring that the intensity in each wavelength interval is calculated directly by integration of the data, with the assumption that the intensity is constant over wavelength inside any pixel which straddles the edges of the indices. Errors introduced by this (common) assumption were found to be negligible.

An absorption line index may be represented in terms of the ratio of the sum of the fluxes in absorption bands to the sum of those in nearby comparison bands, normalised so that the index has a value of unity in the absence of absorption. To avoid problems arising from large-scale errors in the intensity normalisation of the spectrum, all wavelength bands of an index are required to lie within a few × 10 Å of each other.

The index is therefore defined to be

$$I \;=\; \frac{\left(\sum_{i=1}^{N_C}\ \Delta\lambda_{C\,i}\right)\ \sum_{i=1}^{N_A}\ F_{A\,i}}{\left(\sum_{i=1}^{N_A}\ \Delta\lambda_{A\,i}\right)\ \sum_{i=1}^{N_C}\ F_{C\,i}}$$

where $F_{X\,i}$ is the flux in the i^{th} band, these being of width $\Delta\lambda_{X,i}$, and N_X is the total number of flux bands, with $X = A$ indicating absorption bands, and $X = C$ indicating comparison bands.

The values of each of the abundance and gravity indices of Tables 1 and 2 are then calculated for each object of interest, providing the basic observational data from which the metallicity is estimated. Similarly, a set of index values can be computed from the synthetic fluxes. These 16 synthetic indices may be calculated for each of the 100 different stellar models, potentially giving a grid of 1600 data values. Therefore each of the 100 points in the temperature – gravity – metallicity (T_{eff} – log g – [Fe/H]) parameter space has a set of 16 index values associated with it.

2.3 Iron Abundance – Gravity Relations from Indices

As detailed in §3 below, a temperature can be found independently of these line strengths from photometry. Given the effective temperature, one calculates synthetic index values for each of the 16 indices of interest at each point in a grid in a metallicity – surface gravity plane corresponding to the temperature of the star. This may be accomplished by interpolation over temperature for each set of points in the T_{eff} – log g – [Fe/H] parameter space defined by a pair of gravity and metallicity values. The three-dimensional T_{eff} – log g – [Fe/H] parameter space therefore collapses to a two-dimensional [Fe/H] – log g space, with 16 index values being associated with each of the 20 points in the plane.

It now remains to determine numerically the metallicity–gravity relations for each observed index. Given an effective temperature, the value that a particular index may have is constrained to lie in a surface in the three-dimensional index – metallicity – gravity parameter space. If the value of the index I appropriate to that star is determined from observations, the line of intersection between the surface and the plane defined by the observed index can be found. This represents the [Fe/H] – log g relation appropriate to the observed index and temperature of the star. By appropriate interpolations within this three-dimensional parameter space, it is possible to calculate sufficient numbers of ([Fe/H], log g) data points to define the [Fe/H] – log g relation belonging to a particular observed index value, corresponding to the temperature of the star.

These computational procedures could be repeated for each index, establishing a different ([Fe/H]–log g) relation from each. Consequently, a set of 16 relations could be derived. These could be used in principle to solve for the iron abundance and the gravity.

The indices adopted for the analysis were selected on the basis of their sensitivities to metallicity, to gravity, or to both. They may be classed into three broad categories, depending on their relative sensitivities to iron abundance and/or to surface gravity. In the absence of errors in the observational data or in the theoretical spectra, the relations in the [Fe/H] – log g plane obtained from them would intersect at a point, which would define the [Fe/H] and log g values of the star. However, noise in the spectra complicates the analysis. Observational errors in the indices propagate through into the [Fe/H] – log g relations, causing them to meet not at a single point but rather in a region of the [Fe/H] – log g plane, with enclosed area dependent on the noise in the spectrum. The values of the abundance and gravity corresponding to the centre of this region provide the best estimates of the stellar parameters. For the analysis process, the relations

could be plotted in a graph of log g against [Fe/H]. The interactive use of a cursor was adopted as a means of finding the best intersection point based on an eye estimate. Although possessing some subjective qualities, this procedure has the advantage that checks for gross errors can be made, a helpful feature while developing the method, while also allowing the rejection of apparently low-weight data points.

However, the purpose of these analysis methods is the interpretation of low-signal spectra. In this case, the noise in the individual index values will be so large that it becomes difficult to define a solution for iron abundance and for gravity. We therefore combine sets of individual indices having similar sensitivities to abundance and gravity to form *compound indicators.*

A compound indicator is defined in terms of single indices I_1, I_2, ..., I_{N_I}, as

$$C \equiv \sum_{j=1}^{N_I} \omega_j \, w_j \, I_j$$

where C is the compound indicator, N_I is the number of individual indices used, I_j is the value of the j^{th} index used to define the compound indicator, ω_j is the weighting factor given to the j^{th} index, in general inversely proportional to the square of the error in that index, and w_j is a possible additional weighting factor (see Paper I for details).

Three of these compound indicators are composed of indices sensitive to metallicity only, one is made from indices sensitive to both metallicity and gravity, and the final two are made from ionic gravity indices. Provided that the spectrum is not too badly affected by noise, the intersection point of these six indicators in the [Fe/H]–log g plane defines the iron abundance and the surface gravity of a star of interest.

We also defined a single comprehensive compound indicator which could be used to determine the abundance of those stars whose spectra were so noisy that the cursor method could not be applied. This required that a surface gravity be assumed *a priori.*. A single indicator was therefore defined from all eleven indices of Table 1, by giving the metallicity-only sensitive indices additional weighting factors $w_j = 2$, while the metallicity-gravity indices were given weights of $w_j = 1$. This weighting scheme was adopted to reduce the gravity sensitivity of the indicator, while still incorporating those indices which measured very strong absorption lines.

The definition of a second single indicator which combines only those indices which are *insensitive* to gravity can, when compared to the metallicity- and gravity-sensitive compound indicator, provide limited surface gravity information about the stars in the sample. A second comprehensive compound indicator was therefore defined, using the seven gravity-insensitive indices listed in Table 1, with no extra weighting factors.

3. CALIBRATION OF THE EFFECTIVE TEMPERATURE – $(V-I)_C$ RELATION

Our analysis techniques require that the effective temperature be specified as an independently determined parameter. This has the advantage of reducing the number of parameters which are being determined, allowing chemical abundance information to be obtained from even lower signal spectra. We now establish a calibration of effective temperature from $V-I$ photometry.

The analysis techniques were developed primarily to study stars at high Galactic latitudes, along lines-of-sight for which the interstellar reddening is small. In these cases a single color index measurement is sufficient to provide an accurate effective temperature. Although the $(B-V)$ index shows a strong sensitivity to temperature, it also shows a sensitivity to stellar metallicity and, to a lesser extent, to luminosity, reducing its value as a temperature indicator. For example, by interpolation within the data of Böhm-Vitense (1981) to an effective temperature of $T_{eff} = 5000\,\mathrm{K}$, a solar metallicity dwarf has $(B-V) = 0^m.94$, a solar metallicity giant has (B−V) $= 0^m.91$, and a metal-poor dwarf, $\log(Z/Z_\odot) = -1$, has $(B-V) = 0^m.78$.

In contrast, the Cousins' $(V-I)_C$ (Cousins 1976; Bessell 1979) index combines a temperature sensitivity with at most a slight dependence on luminosity and metallicity. As noted by Bessell (1979) for G and K stars, for a given temperature there is little difference in $(V-I)_C$ between luminosity classes III and V. (The dwarf star $(V-I)_C$ – T_{eff} relation determined below will be assumed to apply to all luminosities.) An investigation by Johnson *et al.* (1968) suggests that any changes with metal abundance in the difference in line blanketing effects between the V and I_C bands are likely to be small, producing only a very slight dependence of the $(V-I)_C$ index on metallicity. We confirm this below.

Bessell (1979) provides temperature calibrations for the $(V-I)_C$ and $(R-I)_C$ indices for solar metallicity stars, but does not consider metal-poor dwarfs. We have therefore derived the $(V-I)_C$ – T_{eff} – [Fe/H] relation from published observational data.

3.1 Temperature Data

Effective temperature measurements for late-type stars are available in the literature, including information obtained by comparing spectrophotometric data with model atmosphere predictions, from the detailed analysis of stellar spectra, and using the infrared flux method (Blackwell and Shallis, 1977; Blackwell, Shallis and Selby, 1979). The infrared flux method, which involves comparison of observed fluxes at infrared wavelengths with the integrated stellar flux, has the advantage that it provides results which are insensitive to uncertainties in model atmospheres, although the method is dependent on the absolute calibration of stellar fluxes which is adopted. This method has been used by Saxner and Hammarbäck (1985) to study the temperature scale of F and early G dwarf stars. Measurements were presented for 31 stars with metallicities close to that of the Sun. The stars are in general slightly hotter than is required for

a G dwarf calibration, with $T_{eff} > 5800\,\mathrm{K}$ for all but one. Magain (1987) extended the Saxner and Hammarbäck work to metal-poor stars, presenting temperatures for 11 stars in the range $5300\,\mathrm{K} \leq \mathrm{T_{eff}} \leq 6150\,\mathrm{K}$, $-2.3 \leq [\mathrm{Fe/H}] \leq -1.2$. These two sets of results provide accurate data for the study of early G dwarfs, but they do not cover the entire temperature range required for the F/G stars of interest.

A large body of temperature estimates has been obtained by Peterson and Carney (1979), by comparing observed spectrophotometric distributions with a series of model-atmosphere predictions. They obtained data for 74 dwarfs in the range $T_{eff} = 4760$ to 6300 K, for a wide range of metallicities, in order to perform a calibration of the Johnson $(R-I)_J$ and $(V-K)$ indices. Carney (1983b) provided revisions and additional results, including photometry for the stars. Although the results are model dependent, they form a very useful secondary source of data for the calibration of the $(V-I)_C$ index.

There are eight stars with temperature estimates both from the infra-red flux method and from Peterson and Carney, allowing a consistency check to be made. The mean difference in temperature (in the sense Peterson and Carney minus the infrared flux method) is 16 K, with an root-mean-square difference of 51 K. Thus the two methods indeed yield consistent results and may be combined to construct a set of temperature measurements for the calibration, retaining the temperature estimate from the infrared flux method if available.[3]

3.2 Photometric Data

Photometric observations on the Cousins VR_CI_C system were made by Dean (1981) for some metal-poor stars. Of these, 21 are found to have temperatures from the sources described above. For a few stars, photometry by Taylor (1986) is available. Carney (1983b) published extensive photometric results for metal-poor stars, including most of those having Peterson and Carney temperatures, but the VRI observations have been made on the Johnson system. Fortunately, Carney (1983a) provided a transformation equation relating his $(V-I)_J$ index to Dean's $(V-I)_C$ results, valid over virtually the entire temperature range of interest. This allows Cousins $(V-I)_C$ indices to be calculated from Carney's extensive data, providing a secondary reference source of photometric data. According to Peterson and Carney (1979) and to Carney (1983a), all stars for which they gave temperatures have negligible reddening. Any additional stars are also likely to be sufficiently close to the Sun that reddening can be ignored. The observed color indices are therefore taken to be the intrinsic values for all the stars of interest.

[3] One should bear in mind, however, that King (1993) argues that this temperature scale is too low, by 150–200K, for halo stars.

3.3 Metallicity Data

Metallicity estimates are given for many of the stars in the *Catalogue of [Fe/H] Determinations* (Cayrel de Strobel *et al.,* 1985). Where available, a mean value of the [Fe/H] parameter was calculated from the determinations listed in the *Catalogue,* although the scatter is often quite large. Fortunately the quality of the [Fe/H] data is not critical, as the metallicity dependence of the $(V-I)_C$ index is expected to be small. If no spectroscopic [Fe/H] estimate were available from the *Catalogue,* photometric estimates were derived from the Peterson and Carney $\delta(U-B)_{0.6}$ color excesses using the calibration of Carney (1979), or, when these were not given, color excesses were calculated from the Carney (1983b) UBV photometry and normalised to give the $\delta(U-B)_{0.6}$ parameter by the method of Sandage (1969). Some additional photometric estimates have been taken from the work of Norris *et al.* (1985).

The data collated from the literature are presented in Table 4, listing star identification, $(V-I)_C$, effective temperature and metallicity. Hyades stars were assigned a common metallicity of [Fe/H] = +0.12 . A cross in the 'rejection' column indicates that that star was unsuitable for use in determining the $(V-I)_C$ – temperature calibration.

The quality of the data from the various references varies considerably. Estimates of the stellar effective temperature based on the infrared flux method were favored when available; for color indices, actual $(V-I)_C$ observations were used instead of values calculated from the $(V-I)_J$ index, if possible; for iron abundances spectroscopic measurements were preferred. The orders of preference for the data are summarised in Table 5. A mean was calculated if two or more values of the same reliability were available.

The effective temperature data are plotted against the $(V-I)_C$ color index in Figure 1 in the form of θ_{eff} parameter ($\equiv 5040\,\mathrm{K}\,/\,T_{eff}$), with different metallicity ranges identified. The data are distinguished by [Fe/H]. The trend which is apparent in the Figure may be represented by a linear relation of the form

$$\theta_{eff} \;=\; a \;+\; b\,(V{-}I)_C$$

where a and b are constants. An unweighted least squares fit to the data is shown in the Figure, being

$$\begin{array}{cccc} \theta_{eff} \;=\; & 0.484 & + & 0.581\,(V{-}I)_C \\ & \pm\,0.010 & & \pm\,0.014 \end{array} \qquad (1)$$

Note that consistent values of the fit parameters are obtained by fitting separately those data obtained from the infrared flux method and those from spectrophotometric scans. If the $\theta_{eff} - (V-I)_C$ data are divided into two subsets according to metallicity, unweighted least squares fits to each give

$$\begin{array}{cccc} \theta_{eff} = & 0.491 & + & 0.569\,(V{-}I)_C \\ & \pm\,0.013 & & \pm\,0.019 \end{array} \qquad (2)$$

for [Fe/H]> -1.0, and

$$\begin{array}{rccc} \theta_{eff} = & 0.479 & + & 0.593\,(V-I)_C \\ & \pm\,0.016 & & \pm\,0.022 \end{array} \tag{3}$$

for [Fe/H]≤ -1.0.

These two relations are also consistent with each other to the quoted errors, implying no significant metallicity dependence. Attempts to fit other functional relations which include a [Fe/H]–dependence also fail to reveal any clear sensitivity to [Fe/H]. We conclude that the $(V-I)_C$ – temperature relation is insensitive to stellar metallicity and is well approximated by Equation (1). This relation is valid over the range $T_{eff} = 4500\,$K to $6700\,$K, $(V-I)_C = 0.45$ to 1.1, and has been tested over [Fe/H] $= +0.1$ to -2.7. The scatter of the data points about the relation corresponds to $\pm 90\,$K at $5500\,$K. An error of ± 0.01 in $(V-I)_C$ produces an error in T_{eff} of $\pm 35\,$K at $5500\,$K (propagated errors only).

A comparison of the temperature calibration of Equation (1) with that given by Bessell for solar-metallicity dwarfs reveals that his scale is about 55 K hotter. The difference between his relation and that here for [Fe/H] > -1.0 (Equation 2) is typically only 45 K. Bessell based his calibration on the interferometric results of Code *et al.* (1976) for early spectral types, which extend only to late F-type stars, and on the occultation measurements for K and M giants by Ridgway *et al.* (1980). No data for G dwarf stars were used. Although the calibration presented here does not use the 'direct' methods of temperature determination adopted by Bessell, it has the significant advantage of exploring the parameter ranges of interest in considerably greater detail.

Figure 2 shows a comparison of the relation of Equation (1) with the work of Bessell, and with the theoretical calibration of the $(V-I)_C$ index given by VandenBerg and Bell (1985), which is based on model-atmosphere and synthetic-spectrum computations. For a given $(V-I)_C$ index, the model atmosphere results are hotter than those of the present calibration by between 200 K to 300 K, for stars with [Fe/H] $= 0.0$, and by 150 K to 200 K for [Fe/H] $= -1.0$. The VandenBerg and Bell calculations show a slight, but clear, metallicity dependence in their photometric calibration, amounting to $0^m.02$ in $(V-I)_C$ between [Fe/H] $= 0.0$ and -2.0, for stars having $T_{eff} = 5500\,$K (see Gilmore, Wyse and Jones, 1995). The difference between the colors predicted by the metal-rich and metal-poor calibrations of Equations (2) and (3) is $0^m.01$ for $T_{eff} = 5500\,$K stars. There is therefore a small difference between the temperature scale of VandenBerg and Bell and that of Equation (1).

4. APPLICATION OF THE GENERAL METHOD TO SPECIFIC SPECTRA

4.1 The Available Spectroscopic Data

Spectra were obtained using the Autofib multi-fiber spectrograph of the 3.9-metre Anglo-Australian Telescope, with the IPCS as detector, as part of a radial velocity survey described by Wyse and Gilmore (1990). A total of 60 working fibers were available for program objects and blank sky (4 broken), over a field of view of 40 arcmin. Sky subtraction was achieved to about one percent accuracy, as described in Wyse and Gilmore (1992).

The synthetic calibrations for the analysis techniques are available for wavelength resolutions in the range 1.0 to 2.5Å full-width at half-maximum intensity. The resolutions of the spectra were determined from studies of the arc lamp calibration spectra. Unblended lines were selected which were sufficiently strong that the profiles could be measured accurately, but not so strong that the cores suffered from detector saturation (when the photon arrival rate was so high that the limited time resolution failed to distinguish between successive photons). The full widths at half-maximum intensity were measured for fourteen lines across all wavelengths, independently for spectra from optical fibers at the centre, and at the ends, of the spectrograph slit. The observed wavelength range was 4025–4930Å. For the first fiber on the spectrograph slit, the mean full-width at half-maximum was 2.23 ± 0.07 Å in the 4025–4150Å region, 2.01 ± 0.10 Å between 4500 and 4700Å, and 2.13 ± 0.20 Å between 4840 and 4950Å. The mean value over all wavelengths was 2.11 ± 0.07 Å. For a central fiber, the mean resolution over all wavelengths was 2.12 ± 0.04 Å, negligibly different. The synthetic calibration nearest to this result, that for 2.1 Å, was selected for all analyses of the observational data.

4.2 The Analysis Technique for the 4025–4930Å Region

The general analysis described in Paper I defined optimum indices between 4030 and 5000Å. The available data demanded that the analysis techniques be amended, to accommodate the more restricted wavelength range available, and to use a smaller number of spectroscopic indices. We emphasize here the implications of this change, in order to illustrate the range of applicability of the present technique.

There are nine abundance index flux bands in the list of Table 1 which lie wholly or partly between 4930 and 5000Å. These were used to define four abundance indices. For present application, a revised set of eight abundance indices was defined, as presented in Table 6. These eight indices formed the basis of the analysis techniques as implemented in this Section, for all the observed spectra. Three of the original indices were omitted in entirety (numbers 1, 2 and 4 of Table 1. A fourth index (number 5 of Table 1) was amended by deleting the 4925.8–4931.6 Å comparison flux band. Loss of the 4930–5000 Å region does not affect the ionic gravity indices and those listed in Table 2 were used for the work described below.

To solve for both iron abundance and surface gravity, using the restricted 4025–4930Å region, a set of six compound indicators was defined from the indices of Tables

6 and 2. Three of these compound indicators are composed of indices sensitive to metallicity only, one is made from indices sensitive to both metallicity and gravity, and the final two are made from ionic gravity indices. These are listed in Table 7. Provided that the spectrum is not too badly affected by noise, it is the intersection point of these six indicators in the [Fe/H]–log g plane which defines the iron abundance and surface gravity of a star of interest.

Within the 4025–4930Å region, the single comprehensive compound indicator defined from all indices sensitive to abundance used all eight indices of Table 6. The single compound indicator defined from only those indices which are *insensitive* to gravity consisted of the five gravity-insensitive indices listed in Table 6.

4.3 Estimating signal-to-noise ratios

As discussed in Paper I, the accuracy of an abundance determination depends strongly on the noise in the spectrum. In order to assess the extent of the noise-induced [Fe/H] error, signal-to-noise ratios were measured for the spectra from the scatter of the individual pixel signals about their mean, applying a correction to account for the expected contribution from line absorption (Jones, 1991).

The signal-to-noise ratio per pixel $R_{S/N\,p}$ in a region of the spectrum is given by $R_{S/N\,p} = 1/s_{noise}$, where s_{noise} is the ratio of the standard deviation of the pixel fluxes contributed by noise in the spectrum to the mean flux. However, due to the presence of line absorption, the observed scatter in the pixel fluxes will be larger than that caused by noise alone. On assuming that the effects of line absorption and noise add in quadrature, the observed value s_{obs} of the ratio of the standard deviation to the mean pixel flux is given by

$$s_{obs}^2 = s_{abs}^2 + s_{noise}^2 \ , \tag{4}$$

where s_{abs} is the ratio of the deviation contributed by line absorption alone to the mean pixel flux. The parameter s_{abs} was determined from synthetic spectra, convolved with a representative instrumental resolution profile. A table of s_{abs} as a function of stellar effective temperature and metallicity was generated. Following an abundance analysis, the value of s_{abs} appropriate to any individual spectrum could be determined by interpolation within these data and the value of s_{noise} calculated from the observed scatter of the pixel fluxes using Equation (4). Although tests using noise-added synthetic spectra confirmed the accuracy of this approach, the method was used only if the noise in the spectrum strongly dominated over the effects of line absorption: no attempt was made to derive signal-to-noise ratios if $(s_{obs} - s_{abs})/s_{obs} > 0.15$.

The signal-to-noise ratios within the 4500–4690Å region were used to measure the quality of the spectroscopic data. The ratio of the standard deviation to the mean pixel flux was determined in individual 50Å sections and a mean value of s_{obs} calculated for the entire 4500–4690Å region, to guard against large-scale irregularities in the intensity normalisation contributing to s_{obs}. For a resolution of 2.1Å full-width at half-maximum, the values of s_{abs} range from 0.009 at T_{eff} =6500K, [Fe/H]= -2.0 to $s_{abs} = 0.32$ for solar-metallicity dwarfs with temperature of 4500K.

5. APPLICATION AND CALIBRATION USING STANDARD STARS AND CLUSTERS

Analysing observational data for stars of known chemical compositions allows one to identify and isolate any errors in the calibration of the abundance scale. The synthetic spectra on which the present technique is based were obtained by scaling a standard solar model atmosphere, with the assumption of solar element ratios, which may result in a systematic offset requiring a recalibration, particularly for analyses of stars differing significantly from the Sun in terms of metallicity, temperature and surface gravity.

Tests were performed using spectra of the twilight sky (essentially the solar spectrum), of a selection of stars in the open cluster M67 and of a sample of field stars known to cover a wide range in metallicity. Photometrically-determined effective temperatures were obtained prior to the analysis of the stellar spectroscopic data.

5.1 Analyses of Twilight Sky Spectra

Eight separate sets of 60 twilight sky spectra were analysed, providing a zero-point for the abundance scale. The individual spectra have low signal-to-noise ratios, generally in the range 3 to 18 (for 1.0Å wide bins). Following standard data reduction, the 480 separate twilight sky spectra were coadded to produce a low-noise solar spectrum, which was analysed using both of the comprehensive compound indicators introduced above.

A standard solar surface gravity of $\log_{10}(\,g\,/\,\mathrm{cms}^{-2}) = 4.44$ was adopted. The all-metallicity index comprehensive compound indicator, which includes gravity-sensitive indices, yielded an iron abundance of $[\mathrm{Fe/H}] = -0.14$ for the co-added data, while the metallicity-only index comprehensive compound indicator gave $[\mathrm{Fe/H}] = -0.06$. Thus there is a small error in the zero-point of the abundance scale.

There are several conceivable causes of small errors in the abundance scale. Given the accuracy of the techniques for the reduction of synthetic spectra, numerical errors in the solution for the stellar parameters are unlikely to be so large so as to account for these zero-point problems. Neither should the inaccuracies introduced by the normalisation of the continuum level be on this scale. Deficiencies will be present in the synthetic spectra, due to the use for example of inaccurate gf-values. However, given that the majority of oscillator strengths were computed from the solar spectrum, it is to be expected that these deficiencies will be minimised for solar analyses. The neglect of molecular lines in the computation of the synthetic spectra would tend to underestimate the absorption in both the absorption and comparison bands of the indices, leading to a [Fe/H] result which would be too large, in contrast to the underestimate actually obtained. Similarly, the neglect of large numbers of weak metallic lines not included in the Moore *et al.* compilation would cause an overestimate. That the error of the all-metallicity indicator is greater than that of the metallicity-only indicator might suggest the presence of a problem which is worse for stronger Fe I lines, such as an inability to represent their damping wings correctly. However, again the computation of oscillator

strengths from solar data would avoid such difficulties; only the lines synthesised using published weighted oscillator strengths would be susceptible to this.

The presence of scattered light, which is removed from program stars by the sky subtraction procedure, is also unlikely to be an important source of zero-point error, but will contribute to the random error. As discussed in more detail by Wyse and Gilmore (1992), for the setup typically used for the data aquisition, only $\sim 4\%$ of the flux from one spectrum is scattered into nearby spectra. Uniform scattering adds only 0.2% of the total flux in an image to any one spectrum.

The coadded twilight sky/solar spectrum was then analysed using the six separate compound indicators of Table 7. While the four iron abundance sensitive indicators show only small scatter, the two ionic equilibrium indicators show less consistency. Indeed, a difficulty arises in the use of the ionic indicators in spectra having resolutions as low as the 2.1Å value of the available observational data. The ionic indices were optimised for use in the analysis of spectra having resolutions close to 1.0Å. The flux bands frequently contain only single ionic absorption lines. Consequently the indices are less sensitive to surface gravity for the coarser resolutions considered here. Of the five ionic indices of Table 2, tests with synthetic data reveal that index number 9 does lose sensitivity to gravity as the resolution is degraded, becoming of little use in analyses at a 2.1Å resolution. The other four indices do, however, continue to provide useful information at this resolution.

Having analysed the coadded data, the 480 individual solar spectra were reduced and iron abundances were determined from each. On assuming the solar surface gravity, the mean iron abundance result from the all-metallicity comprehensive compound indicator was [Fe/H] $= -0.17$, with a standard deviation of 0.23, while that from the metallicity-only comprehensive compound indicator was [Fe/H] $= -0.10$, with a standard deviation of 0.25 dex. These are in satisfactory agreement with the results from the higher signal co-added data.

The analyses of the twilight sky data have shown consistently that there is a small zero-point error in the abundance results. This is corrected for by adjusting the output of the all-metallicity comprehensive compound indicator by adding $+0.14$ dex, while those of the metallicity-only comprehensive indicator were adjusted using a correction of $+0.06$ dex. This practice was adopted for all later abundance results.

5.2 Analysis of Spectra of Stars in the Cluster M67

A sample of 74 stars in the old open cluster M67 was used for further tests of the abundance analysis techniques. This cluster offers a selection of well-studied stars which have published photometry by several different authors. Being of the same chemical composition, these stars enable the accuracy of the techniques to be investigated as a function of temperature, and, to some degree, of surface gravity. Spectra were obtained in May 1989 for a number of dwarfs, turn-off stars and subgiants. Cluster stars are known by a variety of different designations, of which those of Eggen and Sandage (1964), Racine (1971) and Sanders (1977) are most common. The Racine naming system is an

extension of that of Eggen and Sandage, and is adopted here. Signal-to-noise ratios in 1.0Å wide bins were in the range 5 to 27, with a majority between 9 and 19.

Cross-correlations of the M67 spectra with standard templates provided the radial velocities which are required for the correction of the wavelength scales to the laboratory rest frame. These radial velocity data also provided a means of testing cluster membership, in addition to identifying some binary star systems. Non-binary members of the cluster should all have similar radial velocities, since the velocity accuracy for our spectral resolution and wavelength range, 5–10 km/s, is considerably larger (by an order of magnitude) than the intrinsic velocity dispersion of the cluster.

An initial test of the suitability of a star for abundance analysis was therefore made by rejecting those having velocities outside a narrow range centred on the mean radial velocity of the M67 sample. The distribution of velocities of the cluster members was well fitted by a Gaussian function having a $1/\sqrt{e}$-half-width of $\sigma = 6\,\mathrm{kms}^{-1}$, which is dominated by the random errors in the cross-correlation results, together with non-Gaussian wings due to non-members and spectroscopic binaries. A membership criterion that a star had to have a radial velocity within 2σ of the cluster mean produced a sample of 62 cluster members and 12 non-members/binaries. Given the relative frequencies of the background and Gaussian velocity distributions, there is a 95 % probability that any given star classified as a member by this criterion is indeed a genuine member of the cluster.

Precision radial velocity results are available in the literature for some M67 stars, allowing a check to be made on the reliability of our adopted membership criterion. Mathieu *et al.* (1986) give such data for 33 stars from the present sample of 74. Of these 33 stars, 26 passed a 2σ velocity test using a mean velocity for the cluster stars and the Mathieu *et al.* error estimates. One of these was rejected as being a spectroscopic binary using the results of Mathieu *et al.* (1986, 1990).

Sanders (1977) performed a proper motion study of stars in the region around M67, providing membership probabilities. Similarly, Girard *et al.* (1989) presented membership probabilities based on proper motions and distances from the cluster centre. The probability distributions of both surveys are strongly bimodal, with clear peaks at low and high probabilities. A 50% membership probability test was applied to the M67 stars having spectroscopic data. It should be noted that because of the highly bimodal distribution, this 50% criterion conservatively rejects non-members, without leaving contamination problems. For a star to be regarded as a cluster member, it had to pass the membership tests using probabilities from both proper motion surveys and also had to pass the radial velocity tests. Our final sample of M67 members contained 44 stars.

Photometry for M67 stars is available from a number of sources, allowing effective temperatures to be calculated with reasonable accuracy. *BV* data were taken from the studies of Eggen and Sandage (1964), Murray *et al.* (1965), Racine (1971), Schild (1983), Sanders (1989) and Gilliland *et al.* (1991). The data were obtained using a variety of techniques. For example, Gilliland *et al.* and Schild used CCD photometry, the results

of Eggen and Sandage and the new data of Sanders were photoelectric, while Murray *et al.* and Racine used photography. It might be expected that the photographic results would be of lower quality. To test this, the $(B-V)$ data of Racine were compared with those of Gilliland *et al.* for a sample of 23 stars in common to both studies. The mean difference (in the sense Racine minus Gilliland *et al.*) was $-0^m.012$, with a root-mean-square difference of $0^m.047$. Therefore, if available, the photoelectric and CCD data were preferred, with mean $(B-V)$ results being calculated if data were available from more than one photoelectric or CCD source. If only photographic photometry was available, the color index was taken from Racine, or if unavailable, from Murray *et al.*

Published photometry exists for M67 stars for other color indices. Cousins $(V-R)_C$ and $(R-I)_C$ data were taken from Gilliland *et al.* (1991), Taylor and Joner (1985, 1988) and Janes and Smith (1984). $(b-y)$ and β data were taken from Nissen, Twarog and Crawford (1987), Anthony-Twarog (1987) and Taylor (1978).

The $(B-V)$, $(V-R)_C$, $(R-I)_C$ and $(b-y)$ data were corrected for interstellar reddening by assuming the $(b-y)$ color excess of $E_{(b-y)} = 0^m.023$ measured using precision uvbyβ photometry by Nissen, Twarog and Crawford (1987). This $(b-y)$ color excess was converted to the $(B-V)$ excess using the $E_{(b-y)}/E_{(B-V)}$ ratio of Crawford (1975). Similarly, the $(V-R)_C$ and $(R-\mathrm{I})_C$ excesses were calculated from the $(B-V)$ excess using data from the Savage and Mathis (1979) interstellar extinction curve. The color excesses adopted were $E_{(B-V)} = 0^m.032$, $E_{(V-R)} = 0^m.015$ and $E_{(R-I)} = 0^m.022$.

A number of different color indices were therefore available for the calculation of effective temperatures. Unfortunately, the available photometric data were sufficiently diverse and disparate that it was not feasible to achieve empirical temperature calibrations from the literature. Insufficient published data were available for M67 stars to define transformations between the different colors and the $(V-I)_C$ index for the calibration of Equation 1 to be used. Instead, theoretical temperature calibrations were used for each of the available color indices. Surface gravities were computed for the stars of interest from published V-band apparent magnitudes. The V apparent magnitudes were converted to absolute magnitudes using a distance modulus of $9^m.71$ (Nissen, Twarog and Crawford 1987). Interpolation within the theoretical isochrones of VandenBerg (1985) for dwarfs, and of Green, Demarque and King (1987) for subgiants, provided the surface gravities corresponding to the absolute magnitudes. Cubic spline interpolation within the synthetic color index calibrations of Bell and Gustafsson (1979, 1989) and of VandenBerg and Bell (1985) gave the effective temperatures appropriate to the dereddened photometry, the calculated gravities and an assumed [Fe/H] of 0.0. An unweighted mean effective temperature was calculated from the individual estimates of each color index. The temperature scale adopted out of necessity for the M67 stars is therefore that of the Bell theoretical calibration, in contrast to the empirical scale of Equation (1). Figure 2 indicates a difference of about 200K between the scale of Equation (1) and the model atmosphere calibration of the $(V-I)_C$ index; adopting a temperature scale 200K cooler would lead to iron abundance measurements for M67 stars 0.16dex smaller.

The spectra were prepared in the standard manner; after the subtraction of the night sky spectrum, the continua were normalised to a constant level and the velocity corrections were applied. The spectra were analysed using both the all-metallicity and the metallicity-only comprehensive compound indicators, as amended for the 4025–4930Å region. The 2.1Å resolution synthetic flux calibration was adopted. The photometric temperatures and the gravities derived from absolute magnitudes were used in the analyses. The zero-point corrections to the [Fe/H] results derived from the twilight sky spectrum were applied.

The iron abundance results provided an excellent test of the consistency of the analysis methods during a study of a sample of stars having a common metallicity. It was possible to search for the presence of systematic errors as a function of temperature. However, the interpretation of the results is complicated by the relatively low signal-to-noise ratios of the spectroscopic data, even by the standards of the methods developed here. Adopting [Fe/H] values from those spectra having signal-to-noise ratios (in 1.0Å bins) $R_{S/N\,1\mathring{A}} > 11$, the mean result was [Fe/H] $= -0.15$ from the all-metallicity comprehensive compound indicator, with an internal error in the mean of 0.03, with $\sigma_{[Fe/H]} = 0.16$. Of the 45 successful [Fe/H] results, 43 had signal-to-noise ratios above this limit. The metallicity-only indicator gave a figure of [Fe/H] $= -0.14 \pm 0.03$, $\sigma_{[Fe/H]} = 0.18$, for the same 43 spectra. We therefore adopt [Fe/H] $= -0.14 \pm 0.10$ as the iron abundance of M67, where the error estimate attempts to account for all error sources, random and systematic.

Figure 3 shows the [Fe/H] results from the all-metallicity indicator plotted against temperature for the subgiants and main-sequence turn-off stars. There is no clear evidence of any temperature dependence in the [Fe/H] results. Figure 4 gives an equivalent plot for the dwarf stars. The dwarfs, however, do not show as constant a result with effective temperature as do the subgiants; the coolest dwarf stars, those with $T_{eff} \lesssim 5300$K do tend to have lower [Fe/H] estimates. A very similar result was obtained by Carney *et al.* (1987; see their Figure 4) in their analysis of low signal-to-noise, high resolution spectra by comparison with synthetic spectra based on Kurucz models. Those models, similarly to the present models, did not take proper account of molecular line absorption, which may be expected to be most important in the cooler stars. Thus any [Fe/H] dependence on temperature seen Figure 4 may well likely be a model artefact.

M67 has had a controversial history of chemical abundance and reddening measurements (Taylor, 1982), with older studies finding metallicities in the range from metal-poor to super-metal-rich. However, in recent years a consensus has been achieved which finds the cluster to have a near-solar metallicity. A selection of recent abundance data is presented in Table 8; the final [Fe/H] result for M67 from this study, [Fe/H] $= -0.14 \pm 0.10$, compares favorably with these results.

This implies that the iron abundance analysis techniques presented here are able to provide accurate results from low-signal spectra.

5.3 Analyses of Spectra of Field Standard Stars

Spectra of a sample of 25 field stars having published metallicity data were obtained in May 1987 and October 1988 using the Autofib system, in a similar manner to the M67 stars. These were selected from the list used by Friel (1987) and from the set of metallicity estimates by Laird, Carney and Latham (1988; hereafter LCL). The six stars considered by Friel had published high-resolution analyses. Of these, three were dwarfs and three were giants. The other 19 stars, having between them 21 individual spectra, had metallicities from LCL, and are expected to be dwarfs on the basis of their selection criteria. These 25 objects cover the [Fe/H] range from +0.4 to −2.9 . Signal-to-noise ratios (for 1.0Å pixels) were in the range $R_{S/N\,1\mathring{A}} = 20$ to 90, higher than for the twilight sky and M67 data. The spectra were reduced in a similar manner to the M67 data.

To ensure consistency with the literature results, the same effective temperatures used in the published analyses were employed. The spectra were analysed using the six compound indicators of Table 7. An eye estimate provided the position of the best intersection point in the [Fe/H] – $\log g$ plane. Each spectrum was then analysed using the all-metallicity comprehensive compound indicator, and again with the gravity-insensitive indicator. Iron abundances were determined by specifying published surface gravities for the stars having high-resolution analyses, or by assuming dwarf gravities for the LCL stars. The results are presented in Table 9 (stars with published high-resolution abundance analyses) and in Table 10 (stars from LCL). One analysis failed: that for G41-41 ([Fe/H] = −2.9) did not return a [Fe/H] – gravity relation, but this is understandable since the star is well outside the metallicity range of our synthetic spectra, being an order of magnitude more metal-poor than the extent of our calculated grid. In adition, the scatter of the [Fe/H]–$\log g$ relations for HD 184266 were too great for a best intersection region to be defined using the six indicator cursor method.

The results obtained with the all-metallicity indicator are compared with the published [Fe/H] data in Figure 5. The error bars in the figure represent the errors estimated from the signal-to-noise ratios of the spectra (see section 4.3 above). The result for HD 218857 is exceptional in differing substantially, by around an order of magnitude, from the high-resolution study abundance by Luck and Bond (1981). No explanation for this difference can be found. G18-55, which was observed twice, provided two abundance results which are inconsistent with the LCL value. The all-metallicity indicator results for this star are not formally consistent : [Fe/H] = -0.46 +/- 0.08 and -0.61 +/- 0.04 . However, the metallicity-only, and six indicator cursor method, results for the two spectra are consistent. G18-55 is, however, a spectroscopic binary (see Carney *et al.* 1994) and on this basis we chose not to use this star to assess the accuracy of the analysis methods.

A comparison of the all-metallicity results from the remaining 23 spectra with the published data gave a mean difference in [Fe/H] of +0.06 (in the sense this work minus literature value), with a root-mean-square difference of 0.24. For the 13 spectra having [Fe/H] in the range 0.0 to −1.2 (the metallicity range of greatest interest to these

analysis techniques), the mean difference in [Fe/H] was -0.04 and the root-mean-square difference was 0.13. Excluding the remaining known binaries from this comparison, *viz.* HD 149414 (Mayor and Turon 1982) and G18-28 (Carney *et al* 1994), changes these numbers only slightly to a mean difference of $+0.07$ dex with rms of 0.25 dex for all 21 stars, and for the stars with [Fe/H] in the range 0.0 dex to -1.2 dex the mean is unchanged, and the rms increases to 0.14

There is some evidence that these techniques overestimate abundances for very metal-poor stars ([Fe/H] < -1.5). However, as the available data are limited for these very low metallicities, we do not make any attempt to recalibrate the abundance scale of the present techniques. In general the results from this work are in excellent agreement with the data from the literature, which have been obtained from high-resolution spectroscopy.

6. CONCLUSIONS

The analysis presented above shows that spectra obtained from fiber-fed spectrographs, despite their unpromising initial impression, are indeed capable of providing a rather accurate estimate of the true iron abundance, with uncertainly ~ 0.2 dex, given an input estimate of the other important stellar parameters, namely the effective temperature and surface gravity. Thus the chemical history of the Galaxy is amenable to study through large surveys of distant stars, without unreasonable requirements of telescope time.

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FIGURE CAPTIONS

Fig. 1 : The θ_{eff} ($\equiv$ 5040K/T_{eff}) temperature parameter plotted against Cousins $(V-I)_C$ color index for the sample of stars of Table 4. Stars are distinguished by metallicity : vertical crosses denote stars having $[Fe/H] > -0.5$, diagonal crosses stars having $-0.5 \leq [Fe/H] > -1.5$, and circles stars having $[Fe/H] \leq -1.5$. The best fitting straight line through the data points (for all metallicities) is shown.

Fig. 2 : A comparison of the temperature scale of Equation 1 with the calibrations of Bessell (1979) and of VandenBerg and Bell (1985). The relation of Equation 1 (solid line) applies to dwarf stars of all metallicites, that of Bessell (triangles) to dwarfs of solar metallicity, while those of VandenBerg and Bell to dwarfs having [Fe/H] = 0.0 (solid circles) and −1.0 (open circles).

Fig. 3 : The iron abundance results plotted against stellar temperature for the objects of the M67 sample classified as subgiants and turn-off stars. Stars are distinguished according to whether they are likely cluster members or binaries (closed symbols for cluster members not known to be binaries, open symbols for binaries and non-members). They are also distinguished according to the source of the photometry (squares for CCD or photoelectric photometry, triangles for photographic photometry only).

Fig. 4 : The iron abundance results plotted against stellar temperature for the stars of the M67 sample classified as dwarfs. Stars are distinguished according to whether they are likely cluster members and by the nature of the photometry used to calculate effective temperatures, with symbols defined as in Fig. 3.

Fig. 5 : A comparison of the field star iron abundance results of this work with published [Fe/H] data. The iron abundance results were obtained using the single comprehensive indicator defined from all abundance sensitive indices. Triangles denote stars having high-resolution analyses, while squares represent those having only Laird, Carney and Latham (1988) metallicities. Open symbols denote visual doubles or stars which are or are suspected of being spectroscopic binaries. Solid symbols denote stars which are not known or suspected of being double or binaries. Error bars represent the predicted noise-induced error in the [Fe/H] results.